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ORIGINAL PAPER

Soil CH_4 fluxes response to understory removal and N-fixing species addition in four forest plantations in Southern China

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Abstract: CH_4 is one of the most important greenhouse gases, and mainly comes from soils in forest ecosystems. The objective of this study was to determine the effects of forest management practices such as understory removal and N-fixing species (*Cassia alata*) addition, on soil CH_4 fluxes in four forest plantations in southern China. Fluxes of CH_4 were measured in *Eucalyptus urophylla* plantation (B_1), *Acacia crassicarpa* plantation (B_2), 10-native-species-mixed plantation (B_3), and 30-native-species-mixed plantation (B_4) stands using the static chamber method in Southern China. Four forest management treatments, including (1) understory removal and replacement with *C. alata* (UR+CA); (2) understory removal only (UR); (3) *C. alata* addition only (CA); and (4) control without any disturbances (CK), were applied in the four forest plantations. The results showed that plantation types had a significant effect on soil CH_4 fluxes. B_1 and B_2 tended to be CH_4 consumers, while B_3 and B_4 inclined to be CH_4 producers. UR decreased CH_4 fluxes by providing a more optimal soil temperature and moisture regime for microorganism community and increasing substrate mineralization. However, CA enhanced CH_4 fluxes in B_1 and B_2 for N-fixing function of *C. alata* while lowered CH_4 fluxes in B_3 and B_4. Soil CH_4 flux rate was significantly related to soil temperature and moisture conditions in the top 10-cm soil layer. Furthermore, the quality of substrates, such as Soil Organic Carbon (SOC) and mineral N might also be important driving factors for CH_4 fluxes. This study improved our understanding on CH_4 fluxes in plantations under different management practices such as UR and CA.

Keywords: soil CH_4 fluxes; forest management practices; understory removal; N-fixing species addition; forest plantation; southern China

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Introduction

Greenhouse gases (GHG) such as methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O) are continuing to increase with unprecedented rates in the atmosphere (Mosier et al. 1998; Baggs et al. 2004). According to the Intergovernmental Panel on Climate Change (IPCC 2001), the globally averaged atmospheric concentration of CH_4 has been increasing at rates of 1.1% in the past decades. Global warming and global climate change have become the most noticeable terms during the past decade (Cox et al. 2000; Giardina et al. 2000; Kirschbaum 2000; Luo et al. 2001; Tang et al. 2003). Although the atmospheric CH_4 concentration (1.8×10^{-6} v/v) is much less than the concentration of CO_2 (370×10^{-6} v/v), CH_4 is 23 times more effective as a greenhouse gas than CO_2 in a period of 100 years (Ramaswamy et al. 2001).

It is noted that a considerable amount of atmospheric GHG is produced and consumed through soil processes and the annual soil CH_4 fluxes have the great potential to influence global climate (Schlesinger et al. 1997). The net CH_4 fluxes between soil and the atmosphere result from the balance between two microbiological processes, which are methanogenesis (production of CH_4) in anaerobic condition and methanotrophy (uptake of CH_4 through oxidation by methanotrophic bacteria) in aerobic condition, respectively (Tate et al. 2007). Understanding of control factors on CH_4 fluxes is critical because relatively small changes in environmental factors may dramatically alter soil CH_4 flux rates (Andrews et al. 2000). CH_4 fluxes are influenced by a number of factors, e.g. soil organic matter (Merino et al. 2004), soil pH (Verchot et al. 2000), soil temperature (Grogan et al. 2004; Song et al. 2006), soil moisture (Subke et al. 2003; Arnold et al. 2005; Wang et al. 2005), depth to the water table (Liblik et al. 1997; Huttunen et al. 2003), N availability (Le Mer and Roger 2001; Kravchenko et al. 2002) and microbial biomass and activities (Fisk and Fahey 2001). Different forest land-use changes and management practices also have significant different effects on soil CH_4 fluxes by altering environmental variables (Houghton

1999; Groffman et al. 2006; Yashiro et al. 2008; Sullivan et al. 2008). Moreover, understory species is a very important component of forest ecosystems, and the species diversity and biomass are controlling factors of soil biota and soil nutrients, but the effects of understory vegetation on CH_4 fluxes are often overlooked.

In China, the total area of forest plantations is about 53.6×10^6 ha, accounting for approximately 30% of the total national forest area of China (China State Forestry Bureau 2005). In southern China, plantation represents a large land use category and most of which are *Eucalyptus urophylla*, *Acacia mangium* and some native species (Xue et al. 2005). In practice, removal of understory or addition of N-fixing species, especially legume species, are common forest techniques in this region for increasing tree growth rate and wood quality (Hu et al. 2007). However, the effects of management practices on CH_4 fluxes in forest plantations are still largely unknown, which are crucial to our understanding and effective management of global CH_4 fluxes (Concilio et al. 2005). To our knowledge, few reports are available on soil-atmospheric GHG exchanges for plantation in southern China. It is important to evaluate the effects of plantation type and forest management practices on soil CH_4 fluxes in southern China.

Therefore, the objectives of this study were to: (1) observe seasonal variations of CH_4 fluxes in four different forest plantations under understory species removal and N-fixing species addition treatments; (2) examine the effects of different forest management practices on soil physical, chemical and biological characteristics in four types of plantations; and (3) understand the main factors controlling the variations of CH_4 fluxes.

Materials and methods

Site description

This study was conducted in the Heshan Hilly Land Interdisciplinary Experimental Station (22°41′ N and 112°54′ E), Chinese Academy of Sciences in Guangdong Province, P. R. China. The climate of the region is subtropical monsoon with a mean annual precipitation of 1 700 mm, falling mainly in the hot and rainy season from April to September. The period from October to March is characterized as cool and dry season. The mean annual temperature is 21.7°C in July with the maximum (39.2°C) and the minimum (0°C) temperature in January. The soil type is Acrisol (FAO 2006). The chemical and physical properties of selected soil at the beginning of the experiment in 2007 are presented in Table 1.

Table 1. Characteristics of four plantations as well as the soils in 2007

Plantations	Age (years)	Tree density (tree·ha^{-1})	Average tree height (m)	Mean d.b.h. (cm)	Canopy coverage (%)	Dominant species*	Soil pH	Soil organic carbon (g·kg^{-1})	Total N (g·kg^{-1})	Exchangeable K (mg·kg^{-1})	Exchangeable Na (mg·kg^{-1})
E. urophylla plantation (B_1)	2	1734	8.9	7.4	0.75	1	4.35	18.17	0.79	16.03	7.09
A. crassicarpa plantation (B_2)	2	1734	4.2	4.8	0.70	2	4.39	22.12	0.75	17.53	6.56
10-species-mixed plantation (B_3)	2	1734	1.4	2.0	0.25	3, 4, 5, 6, 7, 8, 9, 10, 11, 12	4.26	23.13	1.22	24.14	10.27
30-species-mixed plantation (B_4)	2	1734	1.4	1.8	0.30	3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	4.46	17.68	0.88	19.52	7.29

Notes: * 1 is *Eucalyptus urophylla*; 2 is *Acacia crassicarpa*; 3 is *Liquidambar formosana* Hance; 4 is *Magnoliaceae glanca* Blume; 5 is *Tsoongiodendron odorum* Chun; 6 is *Castanopsis hystrix*; 7 is *Michelia macclurel*; 8 is *M. Maudiae* Dunn; 9 is *Jacaranda acutifolia*; 10 is *Sterculia lanceolata* Cav.; 11 is *Dillenia indica*; 12 is *Elaeocarpus apiculatus*; 13 is *C. fissa*; 14 is *M. chapensis*; 15 is *Elaeocarpus japonicus*; 16 is *Ormosia pinnata*; 17 is *Delonix regia*; 18 is *Hedysarum fruticosum*; 19 is *Pterocarpus santalinus* L.F.; 20 is *Dracontomelon duperreranum* Pierre; 21 is *Cinnamomum parthenoxylon*; 22 is *Radermachera sinica*; 23 is *Dolichandrone caudafelina*; 24 is *Garcinia oblongifolia*; 25 is *G. subelliptica*; 26 is *Maesa perlaria*; 27 is *Loropetalum chinensis*; 28 is *Syzygium jambos*; 29 is *Bischofia javanica*; 30 is *Burmann Cinnamon* Bark; 31 is *Machilus chinensis*; 32 is *Quercus dentata*.

Experimental design

The plantations, occupying a total area of 50 ha, were established in spring 2005, and tree saplings were planted at 3 m×2 m spacing. In order to examine the effects of understory species on soil CH_4 fluxes through removing or replacing original understory species, four typical forest plantations were selected for this study. They were 1) *Eucalyptus urophylla* plantation (B_1), 2) *Acacia crassicarpa* plantation (B_2), 3) 10-native-species-mixed plantation (B_3), and 4) 30-native-species-mixed plantation (B_4), respectively (Table 1), and each plantation type has 3 replicates. In total, 12 stands were selected and studied in this study. Major understory species were *Dicranopteris dichotoma*, *Baeckea frutescens* and *Eriachne pallescens* under the four plantations.

In this study, *Cassia alata* was used as the experimental mate-

rial due to its fast growing trait and N-fixing function (Khanna 1997). Four plots (10×10 m each) were established in each selected plantation stand in May 2007 and treatments were randomly assigned as follows: (1) understory species removal and replacement with *C. alata* (UR+CA); (2) understory removal only (UR); (3) *C. alata* addition only (CA); and (4) control without any disturbance (CK). The overall experimental design of this study was a completely randomized design with four forest plantations (B_1, B_2, B_3, and B_4) and four forest management treatments (UR+CA, UR, CA and CK) in each plantation with three replicates. The study was conducted from July 2007 to May 2008.

Measurements of soil CH_4 fluxes

Soil surface CH_4 fluxes were measured with the static chamber method biweekly from June 2007 to May 2008. With the development of technologies, modern instruments such as Infrared Gas Analyzer are introduced for measuring CH_4 fluxes in some current studies, however, the traditional static chamber method associated with gas chromatography is still considered to be a useful and commonly convenient method (Kettunen et al. 2007; Yashiro et al. 2008; Mo et al. 2008).

For this study, simultaneous gas sampling is crucial for accurate parallel comparison of CH_4 fluxes between the four plantations and the four treatments, therefore, all measurements were conducted between 9:00 and 11:00 a.m. daily at two randomly selected points within each plot. It was previously reported that the soil GHG emission between 9:00–11:00 a.m. was closest to the daily mean; therefore, measurement during this period can minimize the observed variability of soil GHG emission resulting from diurnal changes in temperature (Grogan et al. 2004; Tang et al. 2005). Briefly, two polyvinylchloride collars (20 cm in inner diameter, 24 cm outer diameter and 6 cm in height) were first inserted into the soil at about 3 cm in depth. A chamber (22 cm in inner diameter and 20 cm in height) was placed on the collar and gas samples were collected with a 100-mL nylon syringe at 10-min intervals over 30 min. A groove in the collar was filled with water to ensure gas tightness of the chamber. The samples were transferred to the laboratory and CH_4 concentrations were immediately analyzed using gas chromatography (HP 5890) equipped with a 2 m 60–80 mesh 13XMS stainless-steel column (2 mm-inner diameter) under high-pure nitrogen as carrier gas and a flow speed of 30 mL·min^{-1}. Outliers were excluded from the dataset that did not fit the linear change in gas concentrations (R^2<0.7) and the frequency of outliers was 8.3%. The CH_4 flux was calculated according to the following equation:

$$J = \frac{d_c}{d_t} \frac{M}{V_0} \frac{P}{P_0} \frac{T_0}{T} H \tag{1}$$

where, d_c/d_t is the slope of the curve of gas concentration as a function of time, M the mole mass of gas, V_0 the gas mole volume; P is the atmospheric pressure at the sampling site, P_0 the atmospheric pressure under standard conditions, T_0 the absolute temperature under standard conditions, T the air absolute temperate during sampling, and H is the chamber height above the soil surface.

Measurements of environmental variables

During gas samples were taken, relevant soil characteristics such as temperature and moisture were also measured simultaneously at a depth of 10 cm near the collars using a digital temperature probe (Fisher Scientific) and a Theta probe (TK1-Basic, Delta-T Devices Ltd, Cambridge, UK), respectively. Bulk soil samples were collected in September 2007 (rainy season) and March 2008 (dry season) from the soil surface layer (0-10 cm) near each collar. The samples were then air-dried and passed through a 2-mm sieve prior to analysis of soil physical and chemical properties. The soil pH was measured with a 1:2.5 (w/v) ratio of soil to deionized water using a pH meter. Soil organic carbon (SOC) was determined by wet oxidation in an acid dichromate solution, followed by titration with 0.5 N $FeSO_4$ using *o*-phenalphthroline as indicator. Microbial biomass carbon (MBC) was determined by the chloroform fumigation–extraction method (Vance et al. 1987). Fine root biomass (0–2 mm at diameter) was measured by auger boring to soil layer of 10 cm deep. Roots were separated from the soil using a visual inspection of the soil slurry after sieving soil in suspension through a 0.6-mm nylon mesh, and live roots were then distinguished using a dissecting scope (×10) on the basis of color change after staining. The content of NO_3-N and NH_4-N of the soil samples collected in the rainy and dry season was measured. Mineral nitrogen (N) was extracted with 1-M KCl (solution/soil ratio, 5:1, v/v). Slurries were shaken for 1 h at 100 rpm and then filtered (Schleicher and Schuell 5893). The extracts were frozen until analyzed for NO_3-N and NH_4-N with a Bran and Luebbe TRAACS-800 continuous flow analyzer.

Statistical analysis

The statistical analysis was performed using the SPSS 13.0. The normality of variables was checked using Kolmogorov–Smirnov Test. Two-way ANOVA (plantation type and treatment being the main factors) was employed to test for significance. Log transformation was carried out when necessary. The correlation between soil CH_4 fluxes rates and environmental parameters was analyzed. Figures were drawn using SigmaPlot software. In all analyses, the comparison and correlation tests were considered statistically significant (p<0.05). Differences among treatments and vegetation types were compared by LSD test.

Results

Soil physical and chemical characteristics

In the top 10-cm soil layer, significant differences were found among four forest plantations for soil properties such as soil temperature (p<0.05), soil moisture (p<0.01), NO_3-N (p<0.01), fine root biomass (p<0.01) and MBC (p<0.01) (Table 2, Fig. 1), suggesting that treatments had significant effects on these soil

properties, however, little influence was observed for soil pH, SOC and NH_4-N.

Soil temperature and soil moisture exhibited a clear seasonal pattern, higher in the rainy season and lower in the dry season. Soil temperature varied between 12.1–29.0 ºC, 12.1–29.4 ºC, 12.2–32.4 ºC and 11.9–32.3 ºC in B_1, B_2, B_3 and B_4 stands, respectively, while soil moisture varied between 0.8%–30.6%, 2.9%–30.0%, 0.1%–26.4% and 1.2%–28.6% in B_1, B_2, B_3 and B_4 stands, respectively. In all the four plantations, soil temperatures in B_1 (23.0 ºC) and B_2 (23.3 ºC) were significantly lower ($p<0.05$) than those in B_3 (24.1 ºC) and B_4 (24.1 ºC), whereas, soil moistures in B_1 (16.1%) and B_2 (16.7%) were significantly greater ($p<0.01$) than those in B_3 (12.4%) and B_4 (13.5%) during the experimental period (Table 2, Fig. 1A, B). Measured soil temperatures were significantly different between control and treatments, with UR significantly ($p<0.05$) enhancing soil temperature in B_1 (23.3 ºC), B_2 (23.6 ºC), B_3 (24.9 ºC) and B_4 (24.1 ºC) stands during the rainy and dry season. However, soil moisture under UR treatment significantly declined ($p<0.01$) (13.9%, 16.2%, 10.8% and 11.5% for B_1, B_2, B_3 and B_4, respectively) in the four stands (Fig. 1A and B). In contrast, the CA treatment had no significant effect on soil temperature and soil moisture, which is relatively close to CK (Table 2, Fig. 1 A and B).

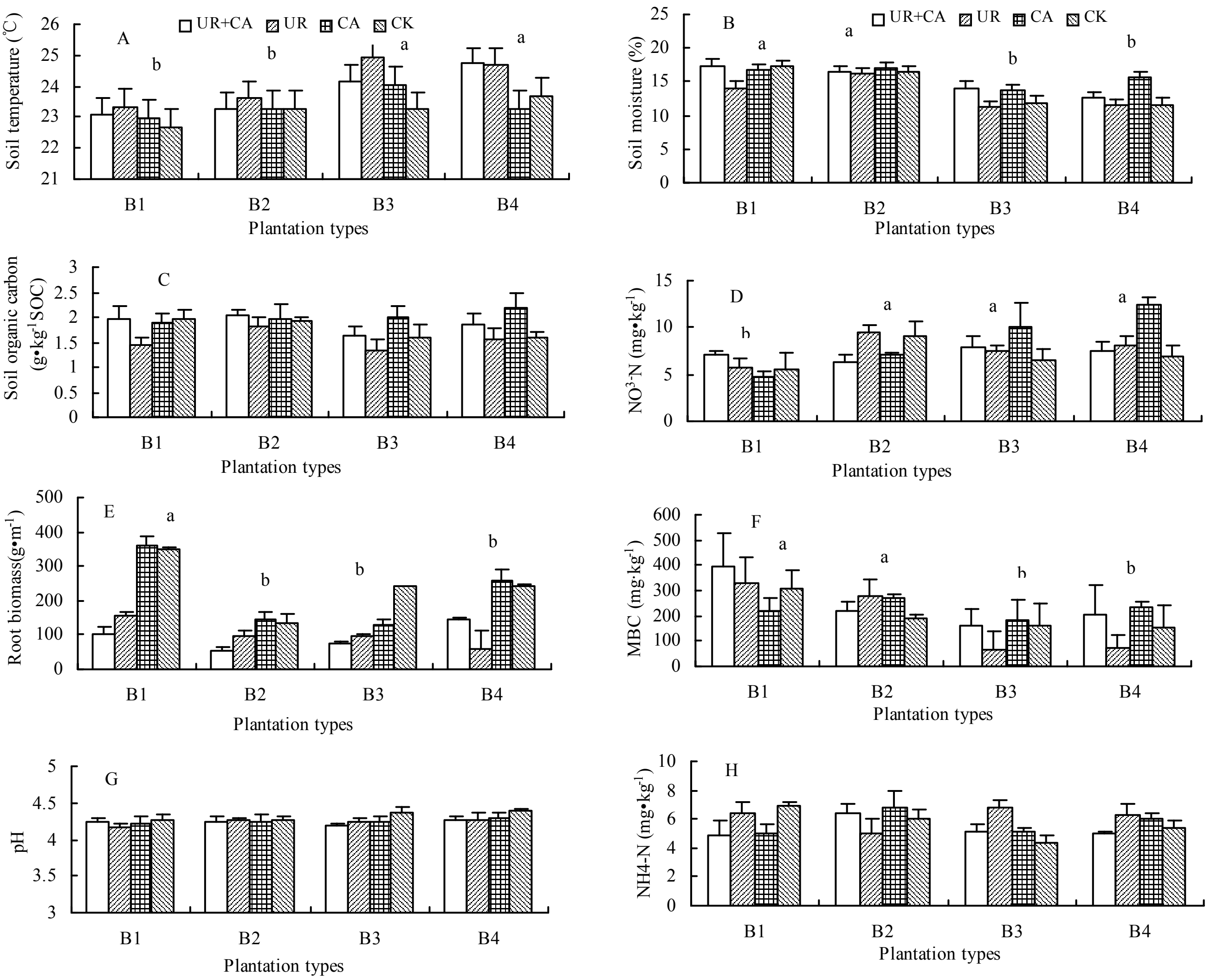

Fig. 1 Measured soil temperature (A), soil moisture (B), SOC (C), NO_3-N (D), fine root biomass (E), MBC (F), soil pH (G), NH_4-N (H), in the top 10cm soil layer in *E. urophylla* stand (B_1), *A. crassicarpa* stand (B_2), ten-species mixed stand (B_3) and thirty-species mixed stand (B_4)

Error bars are standard errors (n=94, 94, 6, 6, 6, 6, 6, 6 for A, B, C, D, E, F, G, H, respectively). Stands superscripted with different letters are significantly different at the P=0.05 level by the LSD test. UR+CA represents understory removed and replaced with *C. alata*; UR represents understory removal only; CA represents *C. alata* addition only; CK represents control.

As regards to soil SOC, no significant difference for SOC was found among four forest plantations, however, as compared to other treatments, UR treatment resulted in a significant reduction ($P<0.05$) in SOC values (1.4, 1.8, 1.4 and 1.6 $g \cdot kg^{-1}$ SOC for B_1,

B_2, B_3 and B_4, respectively) (Table 2, Fig. 1C). *C. alata* addition also influenced SOC in 0–10-cm soil layer, but the effects were not significant (Fig. 1C).

Plantation type also significantly influenced NO_3-N (p<0.01) and fine root biomass (p<0.01). NO_3-N values (5.9 mg·kg^{-1}) were lower, while fine root biomass values (210.0 g·m^{-1}) were higher, in B_1 than those in B_2, B_3 and B_4 (Table 2, Fig 1D and E). NO_3-N in 0–10-cm soil layer was higher in UR+CA, UR and CA than that in CK in the four plantations, indicating significant (p<0.01) difference between treatments and CK (Fig 1D). Fine root biomasses in UR+CA and UR treatments were significantly lower (p<0.01) than those in CA and CK in each plantation because fine roots died after understory harvesting (Fig 1E). There was a significant difference (p<0.05) for MBC among the four plantation types, with an obvious decline found in B_3 (312.6 mg·kg^{-1}) and B_4 (239.5 mg·kg^{-1}), as compared with the other two stands (142.5 mg·kg^{-1} and 173.9 mg·kg^{-1} for B_3 and B_4, respectively) (Fig. 1F). The MBC differed abnormally under UR treatment, which was higher in B_1 and B_2 stands while lower in B_3 and B_4 stands. Furthermore, MBC was significantly (p<0.05) enhanced by *C. alata* addition in this study (Fig. 1F). Neither plantation type nor treatment showed a significant effect on soil pH and NH_4-N in the top 10-cm soil layer (Table 2, Fig. 1G and H).

CH_4 fluxes under different forest management practices in four forest plantations

Although the CH_4 flux rates varied widely during the experimental period, they showed a relatively higher level during the rainy season and then decreased rapidly after November, and a relatively lower level in the dry season regardless of plantation types (Fig.2). The CH_4 flux rates ranged from -66.27 to 59.01μg·m^{-2}·h^{-1}, -37.98 to 75.41μg·m^{-2}·h^{-1}, -54.10 to 69.24 μg·m^{-2}·h^{-1}, and -33.77 to 37.25 μg·m^{-2}·h^{-1} in B_1, B_2, B_3 and B_4 stands, respectively (Fig. 2). CH_4 flux rates in the four forest plantations showed significant differences (p<0.01) by Two-way ANOVA analysis. It could be concluded that soils usually act as the sinks for CH_4 in B_1 (-1.63 μg·m^{-2}·h^{-1}) and B_2 (-3.37 μg·m^{-2}·h^{-1}), while represent as sources in B_3 (2.26 μg·m^{-2}·h^{-1}) and B_4 (9.25 μg·m^{-2}·h^{-1}) (Table 2, Fig. 3). The significant interaction of plantation type and treatment (p<0.01) indicate that the effect of treatment on soil CH_4 fluxes was quite different in the four plantations (Table 2).

Without considering the factor of plantation types, a significant effect of four treatments (p<0.05) on soil CH_4 fluxes was also found in the four plantations over the course of the study, with mean CH_4 flux rates being -1.63, -3.37, 2.26 and 9.25μg·m^{-2}·h^{-1} for UR+CA, UR, CA and CK treatments, respectively (Table 2, Fig. 3). The variations of soil CH_4 flux rates were observed in UR relative to CK in the four plantations, with consistently lower mean values in B_1 (-8.79 μg·m^{-2}·h^{-1}), B_2 (-4.25 μg·m^{-2}·h^{-1}), B_3 (2.41μg·m^{-2}·h^{-1}) and B_4 (5.20 μg·m^{-2}·h^{-1}) stands (Fig. 3). The values under CA treatment tended to be enhanced in B_1 (0.31 μg·m^{-2}·h^{-1}) and B_2 (1.66 μg·m^{-2}·h^{-1}), having higher values in CA than in CK, while the values decreased in B_3 (-2.53 μg·m^{-2}·h^{-1}) and B_4 (7.19 μg·m^{-2}·h^{-1}) stands. In contrast, fluxes of CH_4 showed no conformity of changes under UR+CA treatment during the experimental period, with values of 4.81, -9.76, 1.85 and 12.18 μg·m^{-2}·h^{-1} for B_1, B_2, B_3 and B_4, respectively (Fig. 3).

Relationships between soil CH_4 fluxes and soil properties

The results indicate that soil CH_4 fluxes can be significantly affected by soil temperature and soil moisture, which has been supported by the strong correlations between them as revealed by the correlation analysis (Table 3). Particularly, it has been found that the CH_4 fluxes were strongly correlated to soil temperature and soil moisture in all forest ecosystems. In addition, the CH_4 fluxes were found to be obviously correlated with the soil SOC (r=0. 327) in Table 3, implying that soil SOC concentration may be the important explanatory variables controlling soil CH_4 flux dynamics. In addition, the experimental results also indicated the strong correlation of both SOC with soil temperature and moisture. Furthermore, the correlation analysis revealed an opposite relationship between SOC and NO_3-N (r=0.419, P<0.05). However, no significant correlation between CH_4 fluxes and soil NO_3-N, NH_4-N, fine root biomass and MBC was observed in this study (Table 3).

Table 2. Analysis of variance of soil CH_4 fluxes, soil physical and chemical characteristics in the 0-10-cm soil layer

Variable	Source	n	Mean square	F-value	P-value
CH_4 flux	Plantation (P)	3	13544.79	4.63	0.003
	Treatment (T)	3	8024.73	2.74	0.042
	P×T	9	3104.50	1.06	0.389
Soil temperature	Plantation (P)	3	111.07	3.72	0.011
	Treatment (T)	3	82.28	2.75	0.041
	P×T	9	12.93	0.43	0.918
Soil moisture	Plantation (P)	3	1423.72	18.15	0.000
	Treatment (T)	3	350.05	4.46	0.004
	P×T	9	92.64	1.18	0.303
pH	Plantation (P)	3	0.03	1.10	0.354
	Treatment (T)	3	0.04	1.34	0.268
	P×T	9	0.01	0.33	0.963
SOC	Plantation (P)	3	0.24	1.10	0.357
	Treatment (T)	3	0.63	2.91	0.041
	P×T	9	0.14	0.64	0.762
NO_3-N	Plantation (P)	3	17.47	4.91	0.007
	Treatment (T)	3	17.57	4.94	0.007
	P×T	9	3.87	1.09	0.402
NH_4-N	Plantation (P)	3	0.99	0.73	0.543
	Treatment (T)	3	1.15	0.84	0.482
	P×T	9	2.62	1.92	0.086
Fine root biomass	Plantation (P)	3	41821.86	7.98	0.001
	Treatment (T)	3	78168.95	14.92	0.001
	P×T	9	10910.32	2.08	0.052
MBC	Plantation (P)	3	37150.69	10.62	0.000
	Treatment (T)	3	11692.05	3.34	0.046
	P×T	9	7907.84	2.26	0.074

Discussion

Effect of forest plantation types on CH_4 fluxes

The results showed that plantation type and treatment exerted great effect on soil CH_4 fluxes in the four forest plantations. Soils can either be a net sink or source of CH_4, depending on environmental conditions and plantation ecosystems (Chan and Parkin 2001a; Gregorich et al. 2005; Liebig et al. 2005). As shown in Fig. 2, the CH_4 fluxes during the study period exhibited great fluctuations and regularities. In the four plantations, soil CH_4 fluxes changed with seasons, with relatively higher values around rainy season and slightly lower values during dry season. The subsequent decrease in soil CH_4 fluxes after November is presumably due to the lack of optimal environmental conditions in dry season for roots and microbes in dry season, resulting in a reduction in root respiration and microorganism respiration (Irvine and Law 2002; Zerva et. al. 2005).

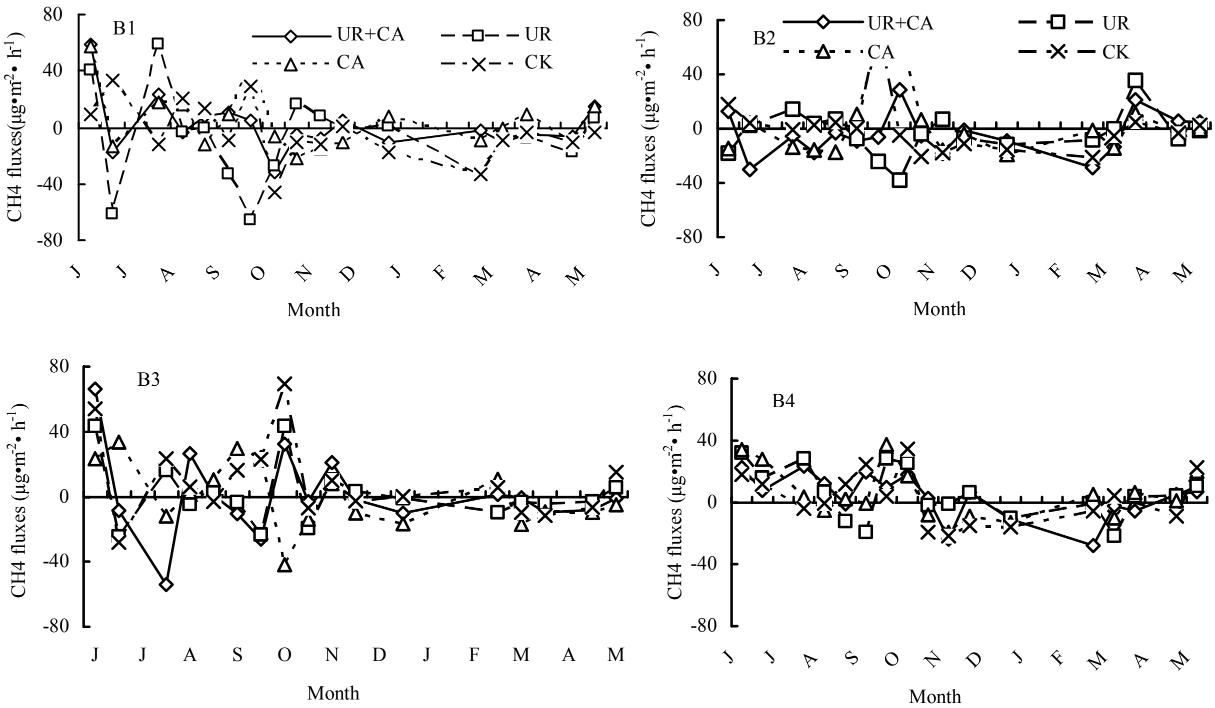

Fig. 2 Monthly variations of CH_4 fluxes in control (CK) and treatment plots (UR+CA, UR and CA) of *E. urophylla* stand (B_1), *A. crassicarpa* stand (B_2), ten-species mixed stand (B_3) and thirty-species mixed stand (B_4) from June 2007 to May 2008

Dots represent means for all chambers at every sampling time. UR+CA represents understory removed and replaced with *C. alata*; UR represents understory removal only; CA represents *C. alata* addition only; CK represents control.

In Table 3, the CH_4 level was positively correlated with the soil temperature, suggesting that soil temperature played an important role in the variation of CH_4 fluxes in the plantations. Tang et al. (2006) reported that CH_4 fluxes were significantly enhanced as soil temperature was increased. Song et al. (2008) reported that CH_4 fluxes were significantly correlated with air temperature and that the temperature affected the annual CH_4 production and emission rates indirectly, via plant and microbial activities. In addition, soil moisture in the top 10-cm soil layer was also an important factor controlling of CH_4 fluxes (Arnold et al. 2005; Wang et al. 2005). In our study, the soil CH_4 fluxes increased as a function of soil moisture (Table 3), which was in agreement with some previous studies (e.g. Song et al. 2008). Significant relationships were found between CH_4 fluxes and soil temperature and soil moisture, however, no conformity of changes was found between CH_4 fluxes and soil temperature and soil moisture in the four plantations (Fig. 1A, B; Fig. 3). Although soil temperature and moisture are strong controllers of soil CH_4 fluxes, CH_4 fluxes were more likely dependent on the response of methanotrophy and methanogenesis on them rather than abiotic factors. Previous studies observed that CH_4 production rates showed a marked dependence on temperature, with optima in the region of 25–30ºC (Dunfield et al. 1993). Dunfield et al. (1993) also observed that CH_4 consumption was optimal in the range of 20–25ºC, and the temperature dependence was much lower than that of CH_4 production.

Significant differences in CH_4 fluxes were found among the four plantations, with CH_4 flux rates being significantly lower in B_1 and B_2 as compared to those of B_3 and B_4 stands (Fig. 3). It is well known that the secretion of CH_4 from the soil occurs during methanogenesis and methanotrophy, and thus is controlled by the soil environmental conditions. The enhancement of CH_4 fluxes in B_3 and B_4 might be attributed to the ease of producing anaerobic micro-zones in the top 10-cm soil layer when the soil moisture is

extremely lower. For the monoculture plantations (B_1 and B_2), *E. urophylla* and *A. crassicarpa* are fast-growing species and their canopies close faster than those of the slow-growing native species in the mixed plantations (B_3 and B_4). This would lead to the direct exposure of the top soil layer to sunshine and high temperature, and thus a fast loss of water was found in B_3 and B_4 during the studying period (Fig. 1A and B). The hardened and impervious soil in B_3 and B_4 might lower the effective O_2 availability in the top 10-cm soil layer (Yashiro et al. 2008), as a result, soil becomes anaerobic and methanogenesis is initiated with more CH_4 being produced (Mayer and Conrad 1990). On the contrary, negative CH_4 flux values in B_1 and B_2 indicated that the top 10-cm soil layer acted as sinks for CH_4 in monoculture plantations. This difference was probably due to relatively lower soil temperature and higher soil moisture, presumably resulting in a reduction in soil bulk density and enhancement in O_2 diffusivity for methanotrophy and higher consumption of CH_4 (Yashiro et al. 2008).

Table 3. The correlation of CH_4 fluxes rate ($\mu g \cdot m^{-2} \cdot h^{-1}$) with soil temperature (ºC), soil moisture (%), SOC ($g \cdot kg^{-1}$), NO_3-N ($mg \cdot kg^{-1}$), NH_4-N ($mg \cdot kg^{-1}$), fine root biomass ($g \cdot m^{-2}$), and MBC ($mg \cdot kg^{-1}$) in each plot

Items	CH_4 fluxes rate	Soil temperature	Soil moisture	SOC	NO_3-N	NH_4-N	Root biomass	MBC
CH_4 fluxes	1.000							
soil temperature	**-0.542***	1.000						
soil moisture	**0.526***	**-0.769****	1.000					
SOC	0.327	**-0.519***	**0.648****	1.000				
NO_3-N	0.180	0.258	-0.165	**0.419***	1.000			
NH_4-N	-0.095	-0.008	0.122	-0.028	-0.006	1.000		
Root biomass	0.319	**-0.550***	0.252	0.194	-0.275	-0.076	1.000	
MBC	0.020	**-0.592****	**0.590****	0.227	-0.331	0.136	0.163	1.000

Notes: Bold numbers indicate significant correlations. **Correlation significant at the 0.01 level. * Correlation significant at the 0.05 level.

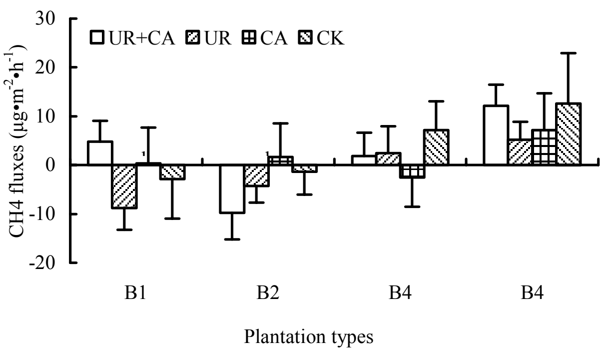

Fig. 3 Comparisons of daily mean soil CH_4 fluxes among 4 plantations, *E. urophylla* stand (B_1), *A. crassicarpa* stand (B_2), ten-species mixed stand (B_3) and thirty-species mixed stand (B_4) from June 2007 to May 2008. Error bars represent one standard error of the mean (n=94). Treatments superscripted with different letters are significantly different at the level of P=0.05 by LSD test. UR+CA represents understory removed and replaced with *C. alata*; UR represents understory removal only; CA represents *C. alata* addition only; CK represents control.

Moreover, some field measurements and indoor experiments all showed that mineral N (NO_3-N and NH_4-N) and MBC were main factors controlling CH_4 emission dynamics (Tate et al. 2007). However, in our study, no significant relationships in plantations were found. The effects of mineral N and MBC on CH_4 fluxes are still unclear and deserve further studies. In summary, though soil temperature and moisture may be the most primary affecting factors on CH_4 fluxes, they may interact with each other and take effect under certain conditions (Chimner and Cooper 2003).

Effect of management practices on CH_4 fluxes

Among the four treatments, there was an obvious and significant CH_4 fluxes during the year. Two-way ANOVA analysis showed that management practices had a significant effect on soil CH_4 fluxes, with UR having the lowest CH_4 fluxes among B_1, B_2, B_3 and B_4 stands (Fig. 3). The effect of UR on soil-atmospheric CH_4 exchanges for plantations in tropical area has not been well studied. A few studies indicated that clear felling could cause a reduction in CH_4 uptake in temperate forests (Steudler et al. 1989; Bradford et al. 2000). Castro et al. (2000) also reported that a shift of the soil from a CH_4 sink to a CH_4 source in two slash pine plantations before and after clear felling. In our study, the change of direction of CH_4 fluxes after UR could probably be attributed to the unavailability of carbon after understory removal and more mineral N produced in the top 10-cm soil layer (Fig. 1C and D). Fig. 1C showed that total SOC content in UR was significantly lower than that in CK. The surface soils were stirred by UR treatment, resulting in decreasing soil C content at the UR stands (Yashiro et al. 2008). Furthermore, due to the removal of understory biomass, UR restricts the continual supply of litter to soils in a certain range. Nakane et al. (1986) reported that the accumulation of the A_0 layer (rich organic matter layer) was decreased after felling because of the lack of litter being supplied to the stand floor.

On the other hand, UR might affect the dynamics of N through alteration of environmental factors (e.g., soil temperature and soil moisture) that control soil N transformation processes (Davidson et al. 2000; Garcia-Montiel et. al. 2001). UR might alter the surface thermal properties (e.g., albedo), energy and

material balances (e.g., solar radiation and precipitation) near the ground, causing changes in soil temperature and soil moisture on soil surface (Zerva et al. 2005). Fig. 1A and B showed that soil temperature was significantly enhanced under UR treatment in B_1, B_2, B_3 and B_4 stands, while soil moisture was significantly reduced under the same treatment. The reason for this difference is that solar radiation and rainfall at the forest floor are directly related to the amount and spatial distribution of vegetative cover in the four plantations (Drever and Lertzman 2003).

The CH_4 uptake from the soil may increase as a result of the increasing mineralization, with the increasing organic matter decomposition rates and greater NO_3-N and NH_4-N concentration in the top 10-cm soil layer (Silvola et al. 1996; Passianoto et al. 2003; Pinto et al. 2004). Fig. 1D showed that NO_3-N concentration was significantly increased under UR in the four plantations. Some previous studies showed that increased N availability could inhibit CH_4 oxidation enzymes (Tlustos et al. 1998) and decrease CH_4 consumption (Bronson and Mosier 1993; Chan and Parkin 2001b). Our results indicated that UR might increase mineral nitrogen (NO_3-N) in the top 10-cm soil layer and increase CH_4 consumption and thereby inhibiting CH_4 production to a certain extent.

In the four plantations, CA treatments exhibited obvious effect on CH_4 fluxes, with higher values in B_1 and B_2, but lower values in B_3 and B_4 as compared with that of CK (Fig. 3). This is in agreement with some previous studies in which that the presence of N-fixing plants was found to be able to decrease the CH_4 consumption (Hergoualc'h et al. 2008). However, Livesley et al. (2008) indicated that this effect was slight and contradictory. It is well known that N-fixing species are able to fix N_2 biologically and have profound effects on soil properties by depositing litter with high N content (Wedderburn and Carter 1999). Fig. 1D showed that NO_3-N in 0–10-cm soil layer was consistently higher in CA than that in CK in the four plantations for the N-fixing function of *C. alata*. It is well known that most of previous studies have been focused on the effect of mineral N input on soil CH_4 fluxes. Laboratory measurements and field studies demonstrated that application of fertilizer N reduces the ability of soil to absorb and oxidize CH_4 (Tlustos et al. 1998; Kravchenko et al. 2002). Castro et al. (1994) reported that an increase in NH_4-N content of soil has an inhibitory effect on CH_4 oxidation through the fertilization, which is arised from the shifted activities of CH_4 oxidizing by methanotrophs. However, the effect of legume species addition might be considered different from nitrogen fertilizer input. In the present study, the soils under CA treatments had more NO_3-N than at the CK sites. Thus, the relatively higher NO_3-N concentration likely had an inhibitory effect on CH_4 oxidation for B_3 and B_4, but an accelerating effect for B_1 and B_2, depending on plantation type or other environmental conditions.

In our result, MBC of the top 10-cm soil layer in CA was relatively enhanced as compared to CK (Fig. 1H), suggesting that MBC and biological activities might also be responsible for the CH_4 fluxes. However, significant relationship was found between CH_4 fluxes and MBC in this study. Therefore, how the fungi influence the emissions of CH_4 still needs further research. Long term measurements of CH_4 would be necessary in order to distinguish the impact of treatments such as CA.

Conclusions

Plantation is a main forest category in southern China. Investigation on the effect of forest management practices such as understory removal and N-fixing species addition on soil CH_4 fluxes is crucial to our understanding and effective management of global CH_4 fluxes. From this study, following conclusions could be drawn:

Forest plantation type has a significant effect on soil CH_4 fluxes. Soil CH_4 fluxes were strong during the rainy season, but weak in the dry season. The top 10 cm soil turned from its role as a net sink of CH_4 to a net source from pure plantations (B_1 and B_2) to mixed plantations (B_3 and B_4). *E. urophylla* and *A. crassicarpa* plantations tended to be CH_4 consumers, while 10-native-species-mixed plantation and 30-native-species-mixed plantation might be CH_4 producers depending on changes of environmental conditions.

Plantation management practices such as UR and CA may exert an important influence on soil CH_4 fluxes, varying with plantation types and structures. For CH_4 fluxes, UR treatment decreased CH_4 fluxes for increased substrate mineralization by providing a more optimal soil temperature and moisture regime for microorganism community. However, CA treatment enhanced CH_4 fluxes in B_1 and B_2 by availability of nitrogen for N-fixing function of *C. alata* while lowered CH_4 fluxes in B_3 and B_4.

Soil CH_4 fluxes rate is significantly related to soil temperature and moisture conditions. Probably, they cooperatively influence soil CH_4 fluxes. Furthermore, the quality of substrates, such as SOC and mineral N might also be the important driving factor for CH_4 fluxes in plantations.

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